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THE 9<sup>th</sup> INTERNATIONAL CONFERENCE ON POSITION SENSITIVE DETECTORS,  
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## Assessment of space proton radiation-induced charge transfer inefficiency in the CCD204 for the Euclid space observatory

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**ABSTRACT:** Euclid is a medium class European Space Agency mission candidate for launch in 2019 with a primary goal to study the dark universe using the weak lensing and baryonic acoustic oscillations techniques. Weak lensing depends on accurate shape measurements of distant galaxies. Therefore it is beneficial that the effects of radiation-induced charge transfer inefficiency (CTI) in the Euclid CCDs over the course of the 5 year mission at L2 are understood. This will allow, through experimental analysis and modelling techniques, the effects of radiation induced CTI on shape to be decoupled from those of mass inhomogeneities along the line-of-sight. This paper discusses a selection of work from the study that has been undertaken using the e2v CCD204 as part of the initial proton radiation damage assessment for Euclid. The experimental arrangement and procedure are described followed by the results obtained, thereby allowing recommendations to be made on the CCD operating temperature, to provide an insight into CTI effects using an optical background, to assess the benefits of using charge injection on CTI recovery and the effect of the use of two different methods of serial clocking on serial CTI. This work will form the basis

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of a comparison with a p-channel CCD204 fabricated using the same mask set as the n-channel equivalent. A custom CCD has been designed, based on this work and discussions between e2v technologies plc. and the Euclid consortium, and designated the CCD273.

**KEYWORDS:** Radiation damage evaluation methods; Radiation damage to detector materials (solid state); Detectors for UV, visible and IR photons

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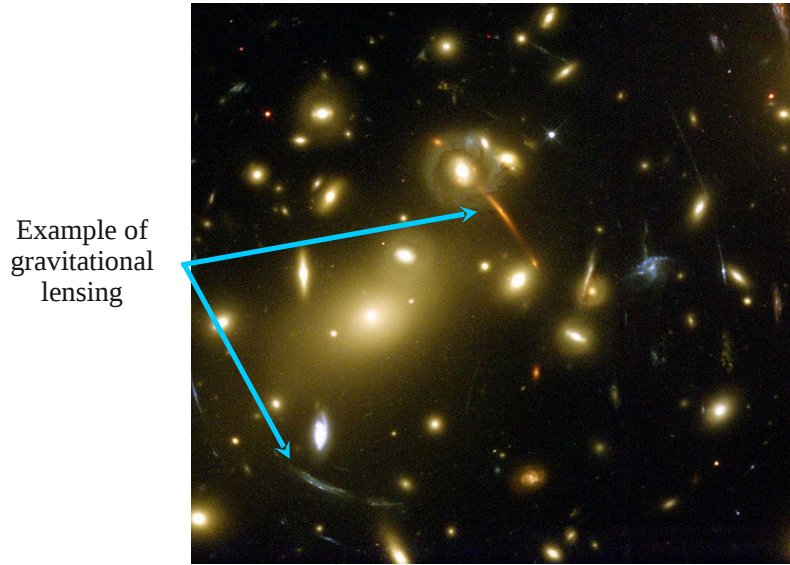
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## 1 Introduction

Euclid is one of three medium class missions belonging to the European Space Agency (ESA) Cosmic Vision plan for launch in 2019; the other remaining candidates for selection are Solar Orbiter and PLATO. Two missions will be selected during the final down-selection in October 2011. Euclid’s primary mission objective is to perform a study of the geometry and nature of the dark Universe by combining several techniques of investigation, including the use of Weak Gravitational Lensing (WL) [1] and Baryonic Oscillations [2]. The payload consists of a single telescope and two instruments, the UK led visible imager (VIS) [3] for which this work has been undertaken and a near-IR photo-spectrometer [4].

Since the 1930’s it has been understood, using accepted theory, that ordinary baryonic particles account for less than 17% of the total amount of matter in the Universe [5, 6]. This has led to speculation into the existence of “dark matter” undetectable using traditional observation techniques [7] or the need for an alteration to accepted theory [8, 9]. An estimation of the amount and distribution of dark matter can be made using the deflection of light by intervening matter concentrations, a process known as gravitational lensing [10]. The effect is illustrated in figure 1. The late 1980’s and early 90’s saw the development of the WL technique [11, 12], which measures the change in ellipticity of galaxies to the order of a few percent. This requires the use of multiple galaxies to calculate the amount and distribution of intervening matter.

Weak lensing measurements from ground based observatories are limited by atmospheric distortions [13] whereas a space based telescope would provide the precision photometry required to analyse background galaxies [14]. The VIS instrument onboard Euclid will allow for an in-depth study into the amount and distribution of dark matter, however, over the course of the five year mission it will be continually bombarded by radiation [15]. The incident radiation will have an adverse effect on the charge coupled devices (CCD) [16] used in the VIS instrument. The radiation induced increase in charge transfer inefficiency (CTI) will lead to the introduction of a systematic error on the shear measurements.



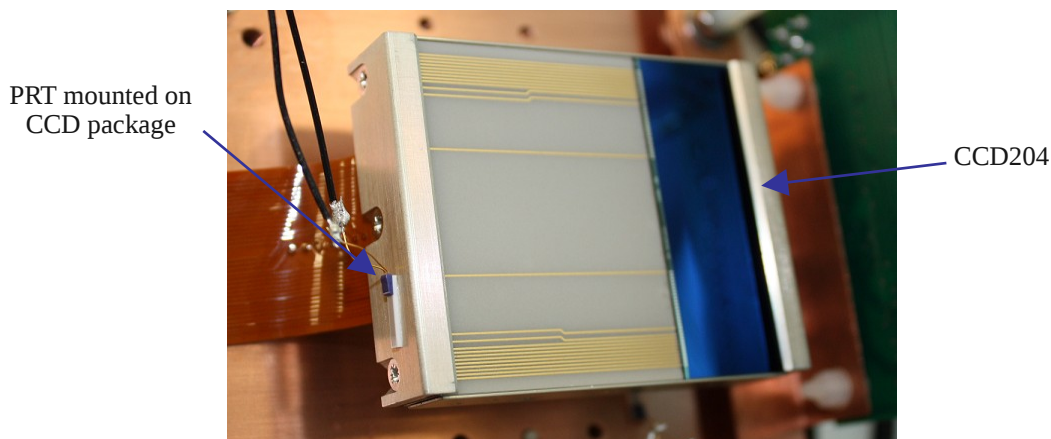
**Figure 1.** Galaxy cluster Abell 2218 captured by Hubble in 1999 [17]

Through an understanding of the radiation damage effects experienced during the mission, through experimental analysis and modelling techniques, the effects of radiation can be decoupled from those of mass inhomogeneities. This paper discusses a selection of work from the study that has been undertaken using the e2v CCD204 as part of the initial proton radiation damage assessment for the Euclid VIS instrument.

### 1.1 Euclid radiation environment

The space radiation environment can be classified into two types, the ‘trapped’ environment and the ‘non-trapped’ or ‘transiting’ environment [15]. Euclid will spend only a short time within the Earth’s radiation belts during its transfer to L2, where it will spend five years subject to the effects of cosmic rays, solar flares and solar proton events. The main source of radiation damage during this period will arise from protons, which form the most abundant charged particle in the transiting environment.

The starting point of any mission related radiation damage study is to estimate the end-of-life proton fluence. The ESA SPace ENVironment Information System (SPENVIS) [18] provides a valuable tool, relating the mission time period, trajectory and detector shielding assumptions to the radiation environment that could be experienced. To provide a worse case end-of-life proton fluence it is assumed that  $\pi$  steradians, as viewed by the CCDs, will have a very limited shielding effect ( $\sim 5$  mm Al) with  $3\pi$  steradians significantly shielded ( $> 20$  mm Al). Using this shielding assumption and the ESP solar proton model with the mission experiencing five years at solar maximum the worse case end-of-life 10 MeV equivalent proton fluence was estimated to be  $6.0 \times 10^9$  protons.cm<sup>-2</sup>. Using a launch date of 2018 provides a 10 MeV equivalent fluence of  $1.5 \times 10^9$  protons.cm<sup>-2</sup>, a factor of 4 times lower than the worse case providing a significant margin to ensure CCD operation is always within mission specification.



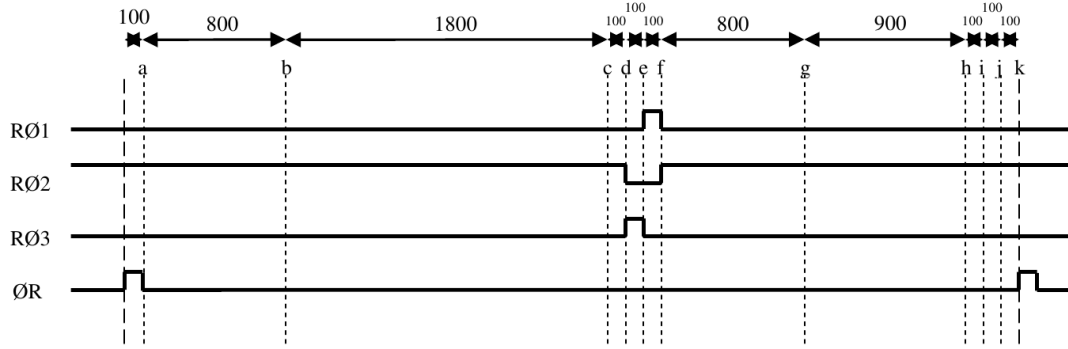
**Figure 2.** A photograph of the CCD204 mounted inside the vacuum test facility

## 2 Experimental arrangement and technique

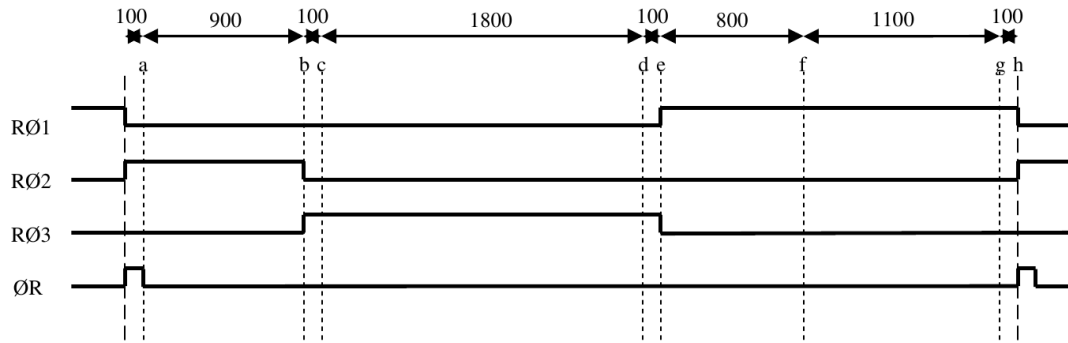
The e2v technologies CCD204 is a radiation test device for the CCD203 used onboard NASA's Solar Dynamics Observatory. The CCD204 possess an image area of  $1064(V) \times 4096(H)$   $12\ \mu\text{m}$  pixels consisting of two imaging areas and output nodes. The device, illustrated in figure 2 mounted inside the Euclid vacuum test facility, also utilises charge injection structures which can be used to injected charge across an entire row of the CCD. The CCD204 was clamped onto a copper cold bench connected to a CryoTiger® refrigeration system with temperature control provided using a Lakeshore 325 temperature controller. An XTF5011/75-TH X-ray tube with a tungsten anode was used to fluoresce a manganese target held at  $45^\circ$  to the incident X-ray beam to provide a known energy (5,898 eV) for calibration and X-ray CTI measurements. Clocking and biasing was provided by an XCAM Ltd. USB2REM1 camera drive box in conjunction with drive software controlled using a custom MatLab software program.

CTI measurements were made using the X-ray technique [19] using 1 X-ray event per 80 pixels and an integration time of 500 s, the Euclid integration time at the time of the study. The effect on CCD performance caused by the diffuse optical background, around  $90\text{ e}^-$  on average, that will be experienced by the CCDs used in the VIS instrument was investigated using an LED. The possibility of extending the life of the CCDs beyond the five year mission through the use of charge injection was also investigated, where charge was injected across the CCD by clocking the input gate, while varying the input diode potential to achieve different levels of injection.

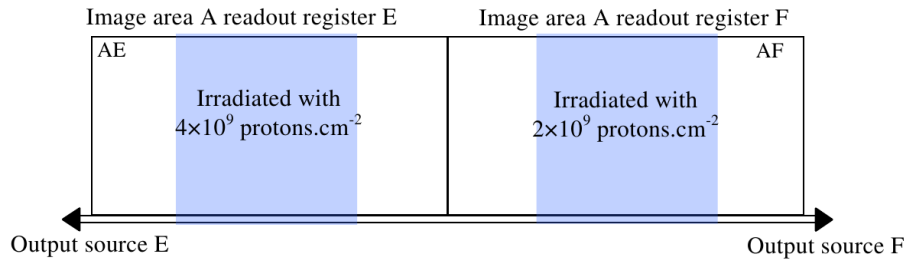
During an initial radiation damage assessment using another CCD204 the burst method of serial clocking was used, illustrated in figure 3, developed to allow the correlated double sampling process to be performed with the same electrode held high. However, the proposed baseline method of clocking the Euclid CCD, illustrated in figure 4, uses video mode clocking. A comparison was performed to investigate the effect on serial CTI. Parallel CTI remains unchanged as both clocking methods use a readout rate of 200 kHz.



**Figure 3.** Clocking scheme used for “burst” mode operation (time in ns)



**Figure 4.** Clocking scheme used for “video” mode operation (time in ns)



**Figure 5.** Diagram of the CCD204, highlighting the areas that were irradiated

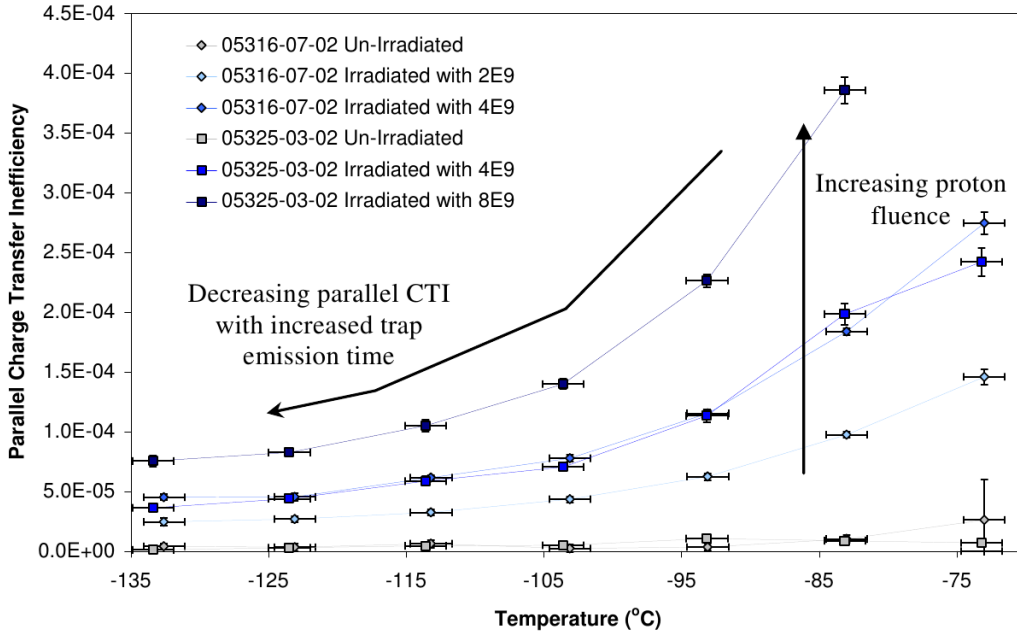
## 2.1 CCD irradiation

Two CCDs were irradiated with protons at the Kernfysisch Versneller Instituut (KVI) in Holland using 50 MeV protons. Two areas were irradiated with a 10 MeV equivalent proton fluence of  $2.0 \times 10^9$  and  $4.0 \times 10^9$  protons.cm<sup>-2</sup> as shown in figure 5, with another CCD irradiated with  $4.0 \times 10^9$  and  $8.0 \times 10^9$  protons.cm<sup>-2</sup>.

## 3 Results and discussion

The first stage of the analysis was to assess the impact of radiation induced dark current and cosmetic defects on CCD performance. A bright defect is defined as any pixel exhibiting charge levels





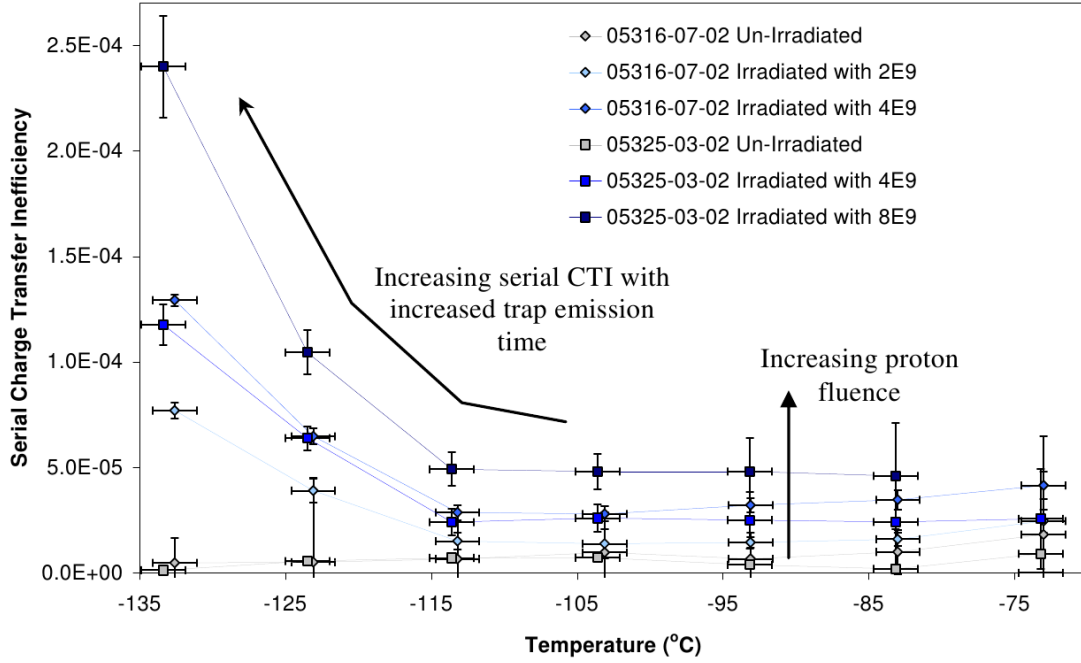
**Figure 6.** Parallel CTI measured as a function of temperature

greater than  $5\sigma$  after a 500 seconds integration time above the mean background level, where  $\sigma$  is the r.m.s. noise in the image. It was found that the contribution of dark current after irradiation would be less than 1 electron at the nominal operating temperature of between 150 K to 165 K and bright defects were no longer identified below 165 K. Based on these results radiation induced dark current and bright defects will not have an adverse effect on CCD performance. Since the completion of this study a cryogenic irradiation has now been performed on a CCD204. Previous cryogenic irradiations indicate an increased number of bright defects prior to the CCD being warmed to room temperature [20], these results and CTI measurements will form part of a future paper.

The second stage of the analysis was to assess the impact of radiation induced increases to CTI on detector performance. Initially the CTI was measured as a function of temperature, with the aim of recommending an operating temperature for use in Euclid and further CCD testing. The CTI is related to the trap emission time,  $\tau_e$ , whereby if the  $\tau_e$  is very much less than the time allowed for trapped charge to rejoin the charge packet,  $t_r$ , and if the  $\tau_e$  is very much greater than the mean time between successive X-ray events,  $t_x$ , the CTI will be low.

The parallel CTI measured in the un-irradiated and irradiated regions of the CCD is illustrated in figure 6. In the un-irradiated regions the CTI is of the order  $\times 10^{-6}$ . Post irradiation the formation of trap sites within the silicon band gap [21] lead to the observed radiation induced increase in CTI. The trend observed as the temperature decreases is as a result of the increase in the  $\tau_e$ , increasing the difference between the  $t_x$  and the  $\tau_e$ . The dominant trap affecting parallel transfer is likely the E-centre. Cooling the CCD effectively freezes out the trap sites minimizing their effect on CTI.

The serial CTI as a function of temperature is illustrated in figure 7 where un-irradiated regions demonstrate a CTI of the order  $\times 10^{-6}$ . Serial transfers occur over a faster time period making serial CTI sensitive to different trap species. The effect of a fast trap becomes evident as the CCD



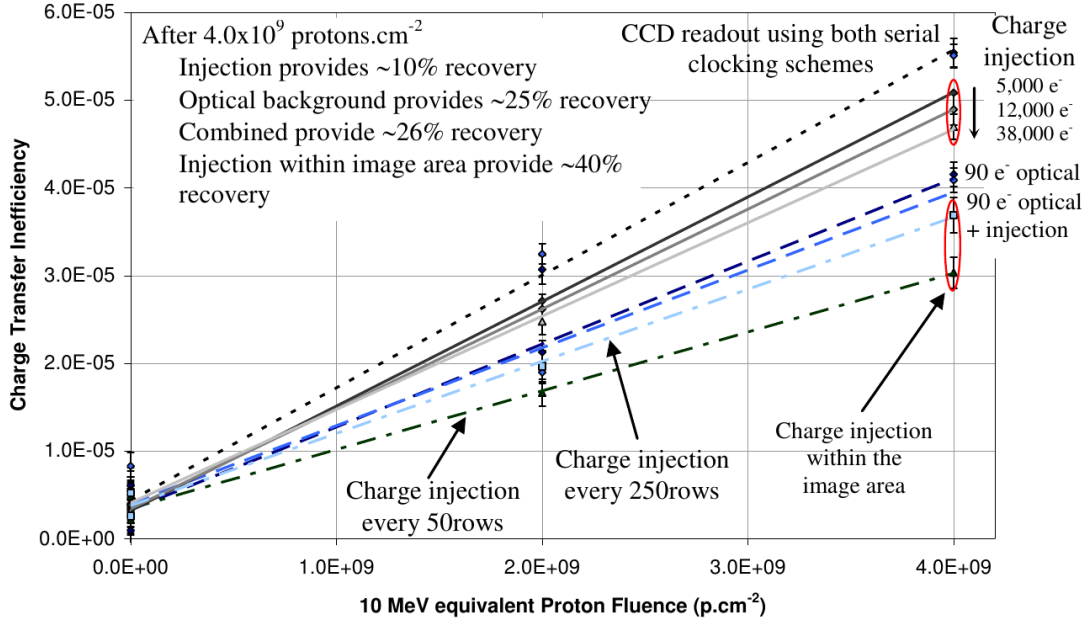
**Figure 7.** Serial CTI measured as a function of temperature

is cooled below  $-113^{\circ}\text{C}$ , likely to be the A-centre as the  $\tau_e$  is no longer very much less than the  $t_r$  and the  $t_x$  and the  $\tau_e$  are comparable.

Therefore to achieve minimum parallel CTI the CCD operating temperature should be as low as possible. However, to minimize the impact of the A-centre on serial CTI an operating temperature of around  $-113^{\circ}\text{C}$  or 160 K appears ideal. Further analysis was then performed at  $-114^{\circ}\text{C}$ , investigating the effects of optical background and charge injection.

The parallel CTI measured as a function of proton fluence is illustrated in figure 8. The addition of the optical background provided around 25% recovery in parallel CTI. This is as a result of the additional charge present in the CCD during the integration period filling traps which would otherwise capture charge from the incident X-ray events. The addition of charge injection of between  $5,000\text{e}^-$  and  $38,000\text{e}^-$ , where the charge is continuously injected then cleared from the imaging area prior to the start of the integration period, provides around 10% recovery in CTI. The improvement in CTI recovery achieved by increasing the amount of charge injected is likely to be the result of the increased probability of encountering and filling traps, the effect is currently undergoing further investigation.

The other method of charge injection relied on periodically injecting rows of  $12,000\text{e}^-$  and holding the rows of injected charge within the imaging area during the integration period. The mean parallel CTI measured across the imaging area is illustrated in figure 8, where charge was injected every 250 and every 50 rows, showing the excellent recovery in parallel CTI. The presence of injected charge during CCD readout ensures that an increased number of trap sites remain filled, with charge incident on the CCD during the integration period essentially “surfing” behind a wall of charge. This method of charge injection would allow for a considerable extension to the CCD operating life. However, it does result in a loss of imaging area due to the rows of injected charge



**Figure 8.** Parallel CTI as a function of proton fluence, measured with and without an optical background of  $90\text{ e}^-$  and using two different charge injection schemes

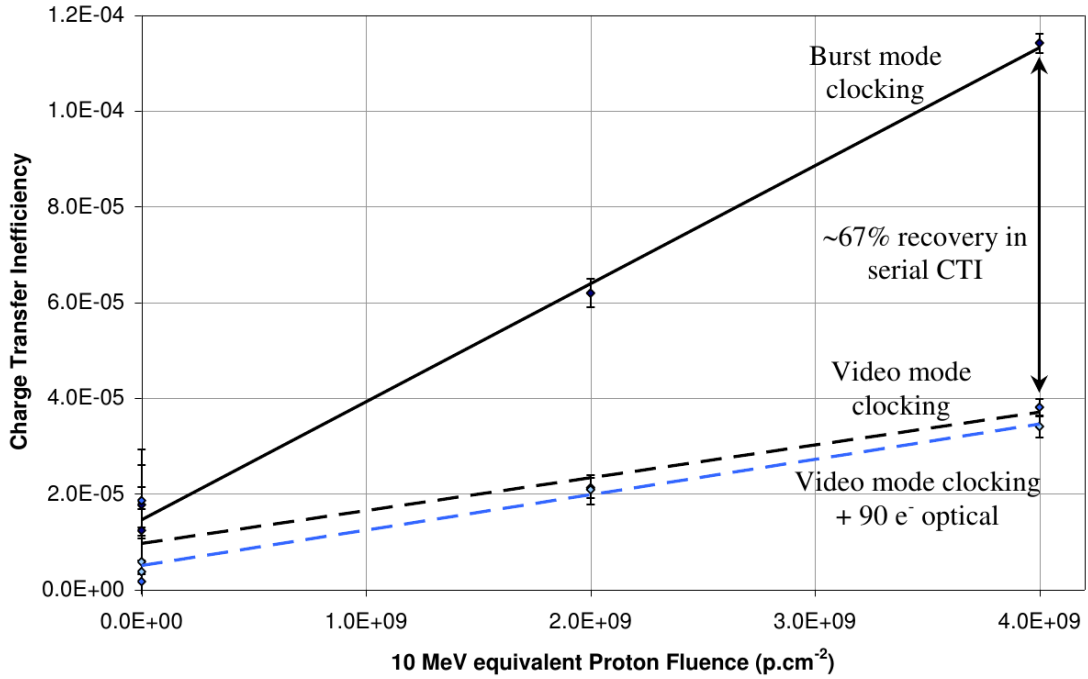
and a differed charge tail (two rows in the case of  $12,000\text{ e}^-$  of injected charge) and the requirement of increased post processing.

The serial CTI measured as a function of proton fluence is illustrated in figure 9. Changing the clocking scheme used from burst to video provides a recovery of around 67% in serial CTI. At this temperature the emission time of the A-centre is around 400 ns, therefore the more even nature of the video clocking scheme increases the probability that trapped charge can rejoin the charge packet. This effect has undergone further investigation using different clocking schemes and will be published shortly. The recovery provided by the diffuse optical background on serial CTI is around 5% and the effect of charge injection is negligible. The reason for this is that the amount of charge travelling through the serial register is considerably higher than within the individual parallel registers, therefore the benefit of additional charge for trap filling is less.

## 4 Conclusions

The measurement of parallel and serial CTI as a function of temperature indicated that the optimal temperature of operation was around  $-113^\circ\text{C}$  (160 K). The nominal operating temperature for Euclid is currently between 150 K to 165 K. The effects of radiation induced dark current and bright defects should not be an issue for Euclid CCD operation. The effect of a cryogenic irradiation on these and CTI effects will form part of a future publication.

The performance evaluation of the radiation induced CTI has provided a high level of confidence in the CCD, and through the use of experimental data being used for charge transfer model verification demonstrated that CTI models will be able to recover galaxy shapes to the required accuracy. The use of charge injection and a worse case end-of-life proton fluence ensures that the



**Figure 9.** Serial CTI as a function of proton fluence, measured using two different serial clocking schemes and with and without an optical background of  $90\text{ e}^-$

CCD operational life is well beyond the nominal mission duration of five years, which will allow the VIS instrument and Euclid to continue to provide a valuable contribution to science well into the future.

Future work includes the comparison of the CCD204 with a custom Euclid CCD, designated the CCD273, designed based on this work and discussions between e2v technologies plc. and the Euclid consortium. The main difference between the two CCDs is the reduction in volume of the serial register, which was estimated to provide a factor of two improvement in serial CTI. This work also forms the basis for a like for like comparison with a p-channel CCD204 fabricated using the same mask set as the n-channel equivalent, to investigate the benefits of p-channel CCDs over n-channel for use in hostile radiation environments [22, 23]. An optical test facility is also currently under development within the e2v centre for electronic imaging at the Open University which will allow for the projecting of Euclid type images onto the CCD to allow the effect of radiation to be investigated further combining experimental and modelling techniques.

## Acknowledgments

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